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HOW PLASTICS REACT UNDER RAPID LOADING

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How Plastics React Under Rapid Loading

High loading rate data are determined by the actual performance of tests in the 5-15 milliseconds to fracture range giving a comparison of mechanical characteristics of high and low rate values on cellulose acetate, cellulose nitrate, nylon, polystyrene, polyethylene and other materials.

Test Method Development

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PLASTICS are more rate sensitive than are some other materials. This, coupled with the fact that many Ordnance Corps items are subjected to very high rates of loading, makes is necessary to know just how these materials will behave when loaded very rapidly. To date, there have been three alternatives. One has been to base predictions of acceptability on data obtained at low rates of loading. This process has been misleading. Another alternative was to fabricate each end item from all available plastics and try each material under use conditions. This proved to be very expensive and time consuming. To avoid the above two processes, efforts have been made to substitute a more easily controlled variable, such as temperature, for the rate. While such a procedure will give qualitative results, the values obtained have not been sufficiently precise for design use.

In recent years, several Laboratories have attempted to obtain data at rates comparable to those achieved in use. The Ordnance Corps' Plastics Laboratory was one of the Laboratories which attempted to do this. A high rate tensile tester was designed and constructed by the Plastics Laboratory of MIT. This work proceeded under the direction of Professors A. G. H. Dietz and F. McGarry. After receipt of the tester, several modifications were made. These changes were incorporated to achieve faster rates, to facilitate testing, and to increase the accuracy of the results obtained.

Results and Discussion

The values obtained at both low ("static") and high rates are shown in Table I. In reviewing these data, emphasis in most cases has been placed on the strength, work to produce yield, and modulus. The first property was chosen for emphasis for the obvious reason that high strengths are normally desirable. Emphasis was placed on work to produce yield for two reasons. One was that most materials are of limited usefulness after they have started to flow. The other was that the work to reach this point (the area under the load-deformation curve up to the yield point) is one indication of toughness or ability to absorb energy. The modulus was chosen since, for some applications, the stiffness of a material will be a critical factor in material selection.

The data shown are the first obtained. Similar data covering all representative plastics will be obtained in a continuing program.

Three cellulose acetates were tested. These were compounded to represent a general purpose, a heat resistant, and an impact resistant material. The data indicate that when a strong tough material is required, the heat resistant grade is superior to the other two grades. The strength of this material is greater both at low and high rates of testing. On the basis of work to produce yield, it is approximately twice as tough as the impact resistant grade. These data indicate that the Izod impact test, which is normally used to measure toughness, does not completely characterize energy absorption ability. They also show that while elongation at low rates is essentially equal for all three grades, an appreciable difference in elongation at yield point appears at higher rates. If stiffness is critical, the general purpose grade is superior although again this would not be evident from the low rate data.

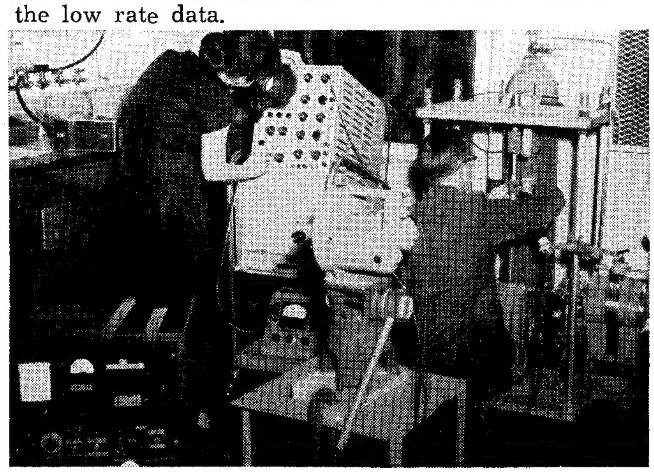

Figure 1. High-rate tensile apparatus showing Fastex camera set-up.

This paper was presented at the 1958 Design Engineering Conference of The American Society of Mechanical Engineers.

TABLE I

	Yield Strength, psi	Elongation at Yield, %	Work to Produce Yield, ft-lbs/ in^3	Maximum Tensile, psi	Elongation at Break, %	Work to Produce Failure ft-lbs/in^3	Modulus psi x 10^3
Cellulose Acetate, General Purpose							
Low Rates	4060	2.25	4.8	4710	27.5	86.8	296.
High Rates	10400	4.2	24.7	10750	13.4	144.	450.
Cellulose Acetate, Heat Resistant							
Low Rates	4380	2.32	5.3	4500	28.8	93.3	311.
High Rates	11400	7.0	46.4	11400	24.2	231.	360.
Cellulose Acetate, Impact Resistant							
Low Rates	1410	2.4	1.7	1410	38.8	37.3	98.
High Rates	4900	5.5	15.0	5050	26.0	97.8	155.
Ethyl Cellulose, Hard							
Low Rates	5160	3.2	9.2	5580	11.9	45.8	303.
High Rates	—	—	—	11500	5.0	31.2	392.
Ethyl Cellulose, Soft							
Low Rates	3930	4.0	9.8	4490	12.1	31.6	224.
High Rates	9400	6.0	31.6	9400	13.4	89.6	380.
Cellulose Nitrate, General Purpose							
Low Rates	4380	3.4	9.7	5260	32.9	120.	311.
High Rates	11600	4.9	33.1	11600	17.3	142.	410.
Cellulose Propionate, Soft							
Low Rates	2090	2.4	2.6	2090	25.3	35.4	128.
High Rates	5500	6.0	36.4	5610	28.5	122.	205.
Cellulose Propionate, Hard							
Low Rates	4580	3.1	7.0	4850	56.0	185.	240.
High Rates	—	—	—	7970	2.3	15.6	330.
Polystyrene, Unmodified							
Low Rates	—	—	—	7450	1.9	6.8	485.
High Rates	—	—	—	9605	2.2	10.6	570.
Polystyrene, Rubber Modified							
Low Rates	3950	5.3	4.0	3950	5.3	13.	243.
High Rates	6350	2.3	7.7	6350	21.1	104.	360.
Polyethylene, Branched							
Low Rates	1300	11.2	8.8	2010	152.	180.	41.2
High Rates	1990	16.0	22.1	—	—	—	42.5
Polyethylene, Linear							
Low Rates	2570	17.1	29.5	3520	28.7	76.8	107.
High Rates	5500	6.9	24.7	5500	13.7	54.9	215.
Polytrichlorofluoroethylene							
Low Rates	5350	7.1	20.5	5350	139.	498.	223.
High Rates	10650	12.4	68.3	10650	55.3	456.	240.
Polyvinylidine Chloride							
Low Rates	3670	12.5	28.	3670	23.3	45.8	107.
High Rates	—	—	—	8810	11.3	31.0	205.
Chlorinated Polyether							
Low Rates	3950	18.5	46.9	4020	62.5	187.	99.
High Rates	8150	9.5	34.2	8420	10.1	50.3	190.
Polymethyl methacrylate, Cast							
Low Rates	9720	5.8	33.3	9720	6.7	41.	434.
High Rates	—	—	—	14000	3.0	15.5	680.
Nylon, General Purpose							
Low Rates	7000	30.3	140.	9900	293.	1580.	147.
High Rates	11100	24.0	191.	11100	127.	934.	360.

A hard and a soft ethyl cellulose were tested. While the hard grade was appreciably stiffer at low rates, the moduli of the two grades were nearly equal at high rates. The hard material did not exhibit a yield so a comparison on that basis is impossible. On the basis of work to produce failure, the soft material appears much better. Thus, in contradiction to the low rate data, the soft grade is nearly as stiff and is much tougher than the hard grade. Strengthwise, the harder material is stronger at both high and low rates.

Only one cellulose nitrate was tested. While this material is normally considered rather tough, these data show that the increase in toughness with rate is not as evident here as with some other materials. However, work, strength, and stiffness all increase with rate.

The cellulose propionates tested show, as did the ethyl celluloses, that the elongation at break is decreased markedly for the hard formulation while the soft formulation is actually more ductile at high rates than low rates. However, contrary to the ethyl cellulose tested, the soft grade did not become as stiff as the hard grade at high rates.

An unmodified polystyrene did not exhibit a yield at either high or low rates. However, the load-deforma-

tion curve obtained at high rates indicated the approach of a yield point. This was unexpected and leads to conjecture as to whether or not even higher rates would result in a true yield. However, at the rates attained in this program, the straight polystyrene was still a strong stiff material with little ductility.

The rubber modified polystyrene shows the same trends as did the unmodified polymer. Strength, elongation at break, work and modulus all increased with an increased testing speed, although the values obtained show that the added rubber increased toughness at the expense of stiffness.

Some differences in the behavior of branched and linear polyethylenes were brought out in this program. Low rate tests indicate that the linear material is much tougher up to the yield point. However, at high rates, approximately equal toughnesses are shown. The data obtained in this program also show that the stiffness of the linear material increased with rate whereas the branched material has equal moduli at the two rates. The extension of the branched material was too great to be obtained with the procedure used.

Polytrichlorofluoroethylene is a tough material as shown by the work to produce yield. While not as tough on an absolute basis as is nylon, the increase from the low rate value is over 300% while for nylon, the increase is only approximately 33%. Stiffness is moderate and is not greatly affected by rate.

Polyvinylidine chloride was stronger and stiffer at high rates but the work decreased.

A chlorinated polyether showed the normally expected increase in strength and decrease in extension. This made the material less tough and approximately twice as stiff.

Cast polymethyl methacrylate showed up as having the highest tensile strength of the material tested. It was also extremely stiff at both high and low rates. The energy absorbing ability is very low, however.

The nylon tested had a rather low increase in work to produce yield as the rate was increased. While it is still the toughest material tested on an absolute basis, the trend would lead to speculation that the advantage of this material might disappear if tested at a sufficiently high rate. Normally, when nylon is tested at low rates, it passes through a yield point, flows, and then rises to an ultimate strength which exceeds the yield strength. This has at times been attributed to orientation. However, at high rates of loading, the yield and ultimate strengths are equal. It may be that the duration of the test is too short to allow orientation.

As stated before, these data were obtained as part of a continuing program. In addition to their value to the design engineer who has an end item which will be subjected to loading in comparable times, they suggest other programs to confirm or refute hypothesis advanced as a result of these data.

Equipment

The equipment used for the high rate testing is shown in Fig. 1. In essence, a piston which is actuated by compressed nitrogen gas is attached by means of a grip to one end of a standard ASTM Type I tensile specimen. There are two alternative routes for this gas. The highest rates are achieved by passing the gas through a solenoid to the piston by the shortest possible route. Slower rates may be obtained by the use of an alternate route containing both a solenoid for the rapid release of the gas and a needle valve to control the rate of flow.

The piston which the gas actuates is contained in a cylinder which has slots machined in the sides. These

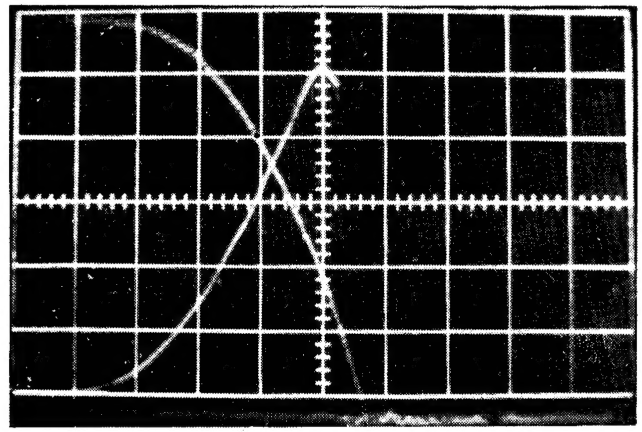

Figure 2. Displacement-time curve (upper) as recorded by potentiometer type pick-up device.

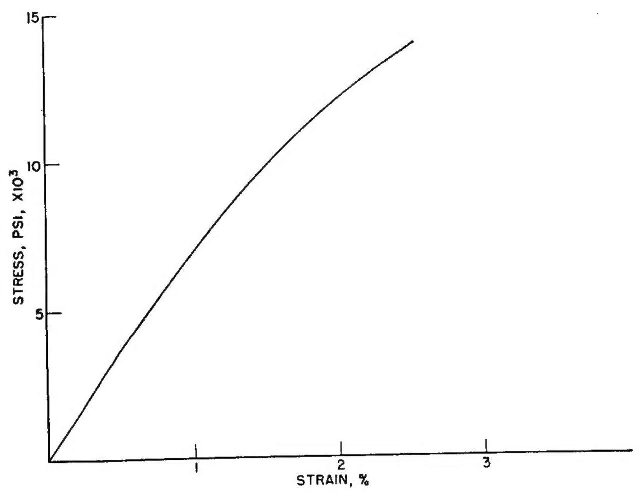

Figure 3. Typical stress-strain curve as constructed from load-time and deformation-time data.

slots are so located that at first, all of the gas is confined by the piston cylinder walls. After the specimen has broken and the upper face of the piston has passed the tops of the slots, gas begins to escape through the slots. When the piston has traveled seven inches, it starts to compress the air in the closed bottom part of the cylinder so that an air cushion is formed to brake the motion of the piston.

The load versus time information is obtained by means of SR-4 strain gages attached to a cylindrical weigh bar. The weigh bar, in turn, is attached to the upper portion of the specimen by means of the upper grip. The output voltage of these strain gages is amplified and fed into an oscilloscope, where a load-time trace is recorded by Polaroid camera.

The measurement of strain offered several difficulties. The original idea was to attach SR-4 strain gages to the specimen and to thus pick up changes in output voltage as the strain increased. However, due at least in part to the small cross-sectional area of the original specimen used and to the effect of the solvents in the adhesives, strain measurements which were in error by 12 to 90% were obtained.

A second approach was to attach a rack to the lower grip and a pinion to a ten turn helipot. The movement of rack actuated the pinion affixed to the shaft of this pot. The change in resistance of this helipot with grip displacement was fed to the oscilloscope and resulted in a time-displacement curve. However, as shown in Fig. 2, the displacement lagged behind the

load by approximately one millisecond. This lag was not constant so that a simple correction factor could not be applied. In addition, the cross head motion rather than the extension in the gage length was being recorded.

It was decided that the only reliable method known was the photographing of the separation of gage marks. Gage marks were applied to the specimens and their separation as the load was applied was recorded by high speed photography. Timing "pips" were also placed on the film so that displacement versus time was recorded.

The black box in the foreground of Fig. 1 controls the sequence of the triggers used. It first starts the camera and turns on the flood lamps so that the camera is up to full speed and the lights have reached maximum intensity before the testing machine is automatically triggered. Suitable delays are incorporated so that the oscilloscope trace and the Polaroid camera are triggered to catch the action. With load-time pictures and displacement-time films, the values can be converted to stress and strain and plotted. A typical plot is shown in Fig. 3.

In this set of experiments, a nitrogen pressure of 1500 psi was used. This gave breaking times of from 2 to 15 milliseconds, depending upon the characteristics of the material being tested. A check on the modulus obtained with the high rate tester was made by dynamic means as described in the May 1956 *ASTM Bulletin*, ("A Vibrating Reed Test for Plastics" by Stephen Strella.).

The low rate data with which the high rate data are compared were obtained using an Instron Universal Testing Machine.

This machine had previously been modified as described in the January 1957 *ASTM Bulletin* ("A Mechanism to Operate a Tension Tester at Constant Strain Rate" by Stephen Strella). These data are of interest in their own right since they were obtained at constant strain rate rather than the more conventional constant crosshead separation or constant rate of load increase.

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Reprinted from SPE Journal December, 1958.